

# **Comparisons of CFD Simulations of Icing Wind Tunnel Clouds with Experiments Conducted at the NASA Propulsion Systems Laboratory**

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# Outline

- Introduction/Objective
- Experiment description
- Model development description
- Simulation evaluation with experimental data
- Summary

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# Introduction – Why Study Engine Icing?

- Numerous events of power-loss and engine damage since the 1990s
- Engine icing studied at NASA (from full scale engine to fundamental studies at PSL)
- **NASA's Goal**: Gather data to develop & validate computational icing tools to predictively assess the onset & growth of ice in current and future engines during flight
  - Requires good data

# Simulate PSL Tunnel for Better Results

- Conditions at the tunnel inlet are known, but conditions are not known at exit plane (test section)
- Efforts made to measure conditions at exit plane
- Previous simulation efforts investigated flow and particle behavior using rigid particles (Feier, 2019)
  - Cloud concentration, but spray bars generate vortex shedding, and large scale vortices downstream dispersing particles
- Activation of the cloud at PSL thermodynamically interacts with the flowing air
- Desire to know the aero-thermal and cloud conditions more accurately at the tunnel test section
- TADICE (1D) developed to simulate the tunnel by thermodynamically coupling the flowing masses
- 1D model cannot explain measured radial variations

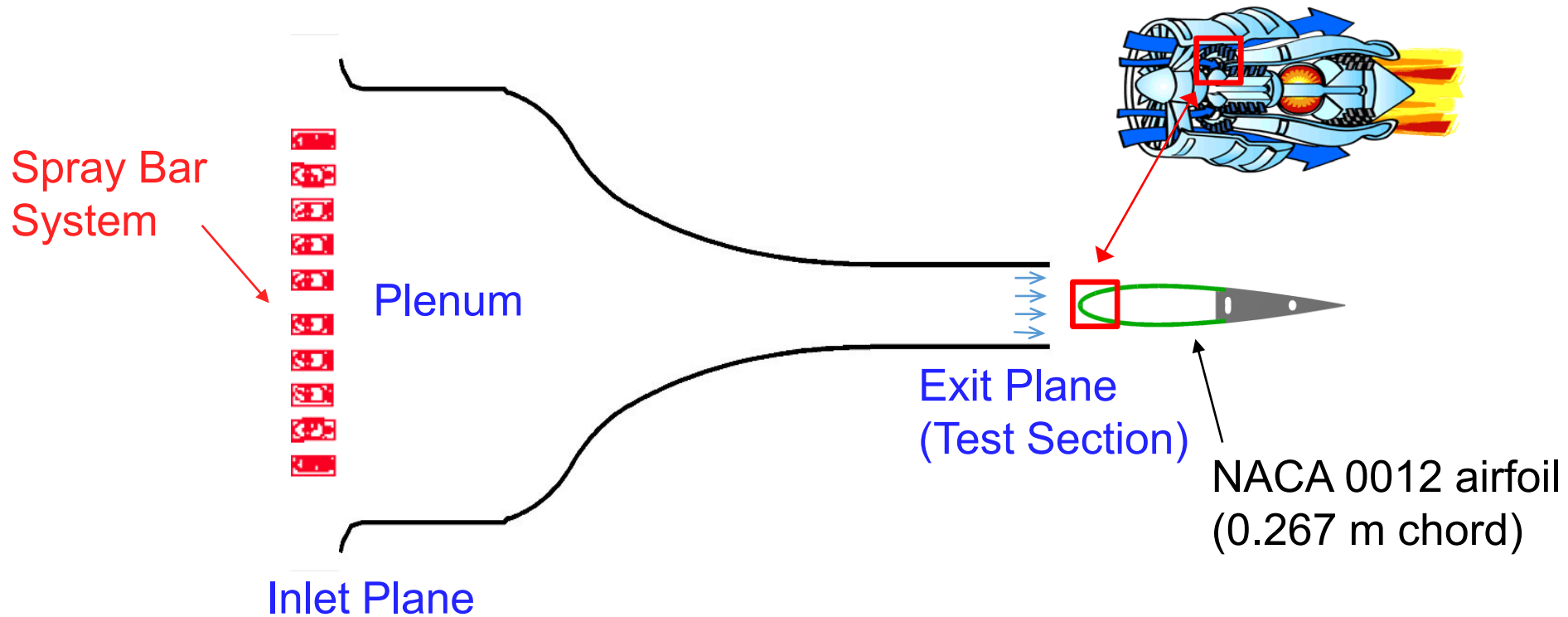
# Objectives

- Develop fully coupled 3D CFD model of the PSL icing wind tunnel
  - Explain change in aero-thermal and cloud conditions measured experimentally
  - Explain radial and circumferential variation
- Compare simulation predictions with experimental measurements (cloud water content, humidity, air temperature) at tunnel exit plane

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# NASA 2018 Fundamental Physics ICI Tests

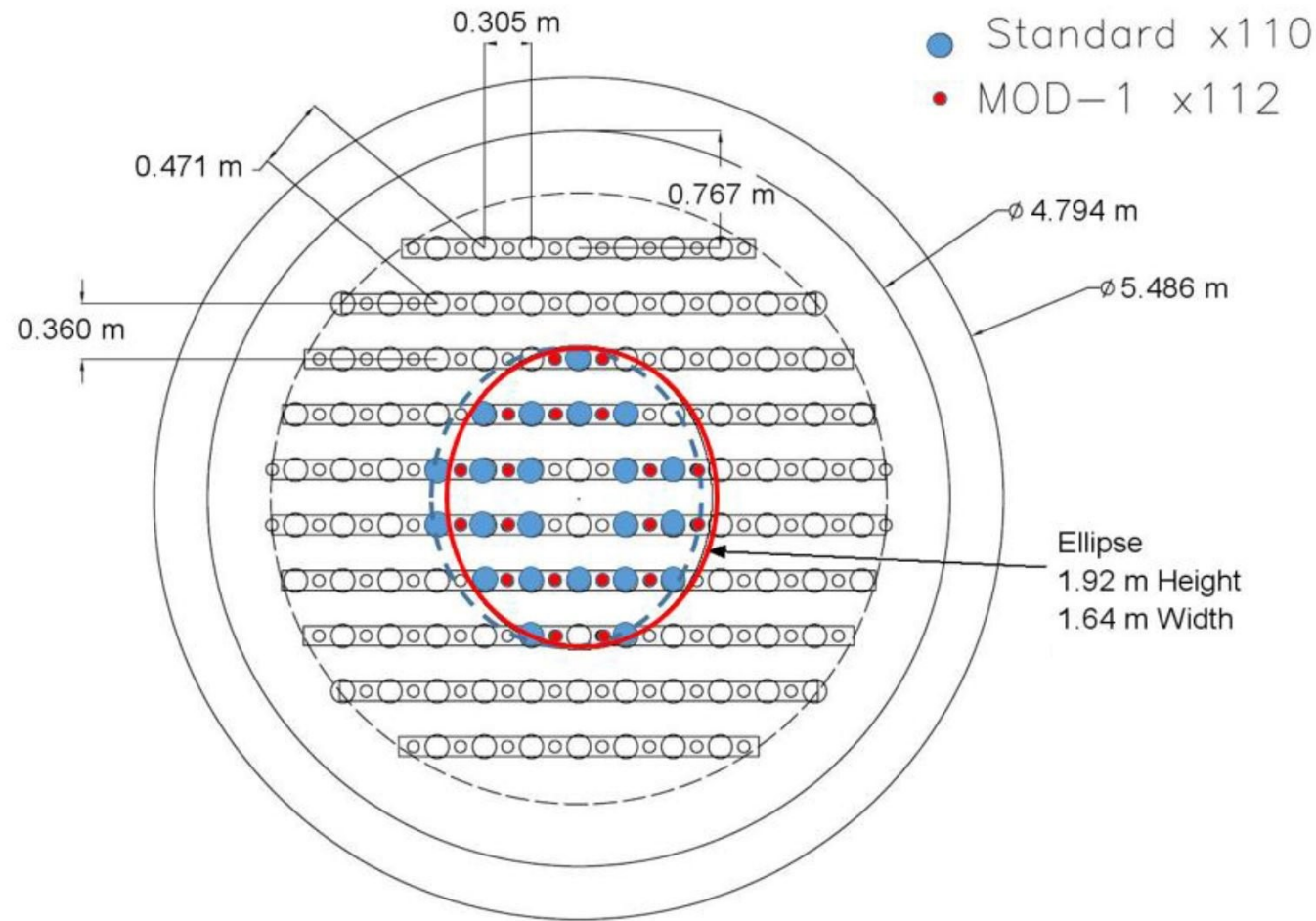


## Goals:

1. Generate a prescribed mixed-phase icing condition with a well-characterized test section (air temp, humidity, pressure, cloud particle size, cloud melt ratio, etc.)
2. See how ice accretion varies by changing a condition and understand underlying physics



# Spray Nozzle Configurations



## Cloud Objectives:

1. Maintain the center  $0.15$  m (6 in) diameter area approximately uniform at the test section
2. Contain the entire cloud within an approximately  $0.61$ -m (24-in) diameter area (tomography used)

# Test Conditions

Test Condition #	$U_e$ m/s	$p_o$ kPa (psia)	$T_o$ °C	$RH_o$ %	$TWC_{e,bulk}$ g/m <sup>3</sup>
I	85	44.8 (6.5)	7.2	34	2.2
II	135	44.8 (6.5)	7.2	33	2.0
III	185	44.8 (6.5)	7.2	33	2.1
V	135	44.8 (6.5)	7.2	35	5.0

## Notes:

- Value of  $TWC$  as calculated for area of 24" diameter at test section, assuming no mass loss to evaporation
- Initial  $MVD = \sim 20 \mu\text{m}$  for all tests
- Initial water temperature =  $7.2 \text{ }^\circ\text{C}$
- Wet-bulb Temperature  $< 0 \text{ }^\circ\text{C}$

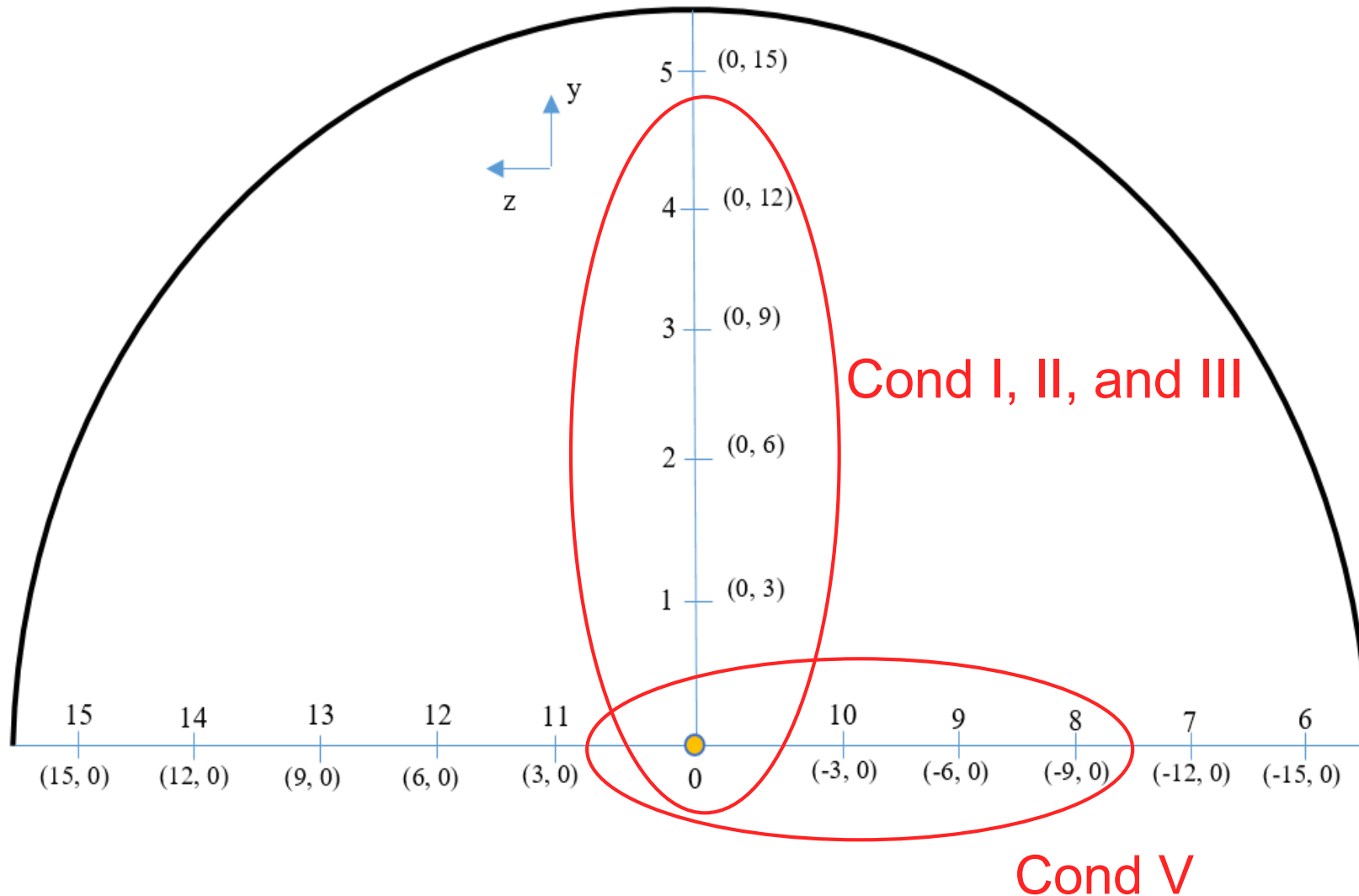
# Instruments

Instrument (Abbreviation)	Measurement
Multiwire probe (MW)	Total Water Content
Isokinetic Probe, version 2 (IKP)	Total Water Content
Tomography (Tomo)	Total Water Content / Cloud Uniformity
Isokinetic Probe, version 2 (IKP)	Humidity
Rearward Facing Probe (RFP)	Humidity
Rearward Facing Probe (RFP)	Total Air Temperature
Rosemount Total Air Temperature Probe (TAT)	Total Air Temperature

- **Ice Crystal Detector (ICD)** – TWC, melt ratio
- **High Speed Imaging Probe (HSI)** – Particle size distribution
- **Phase Doppler Interferometer (PDI)** – Particle size distribution

} Not utilized in this paper

# Instrument Probing Locations (Tunnel Exit)



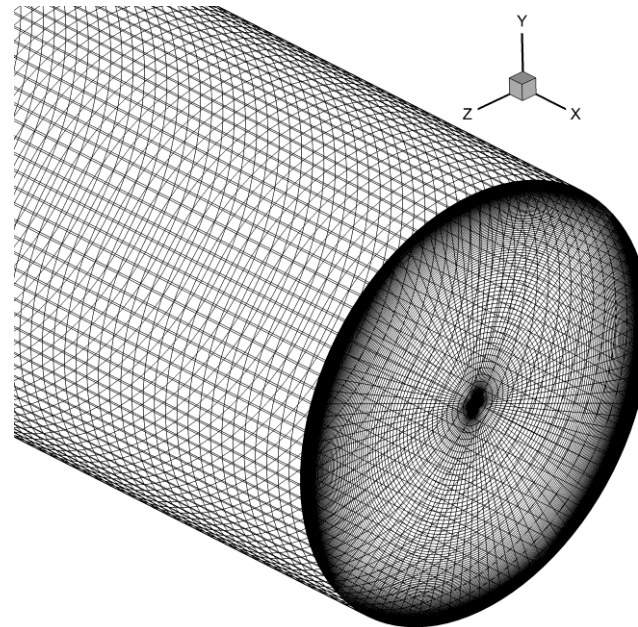
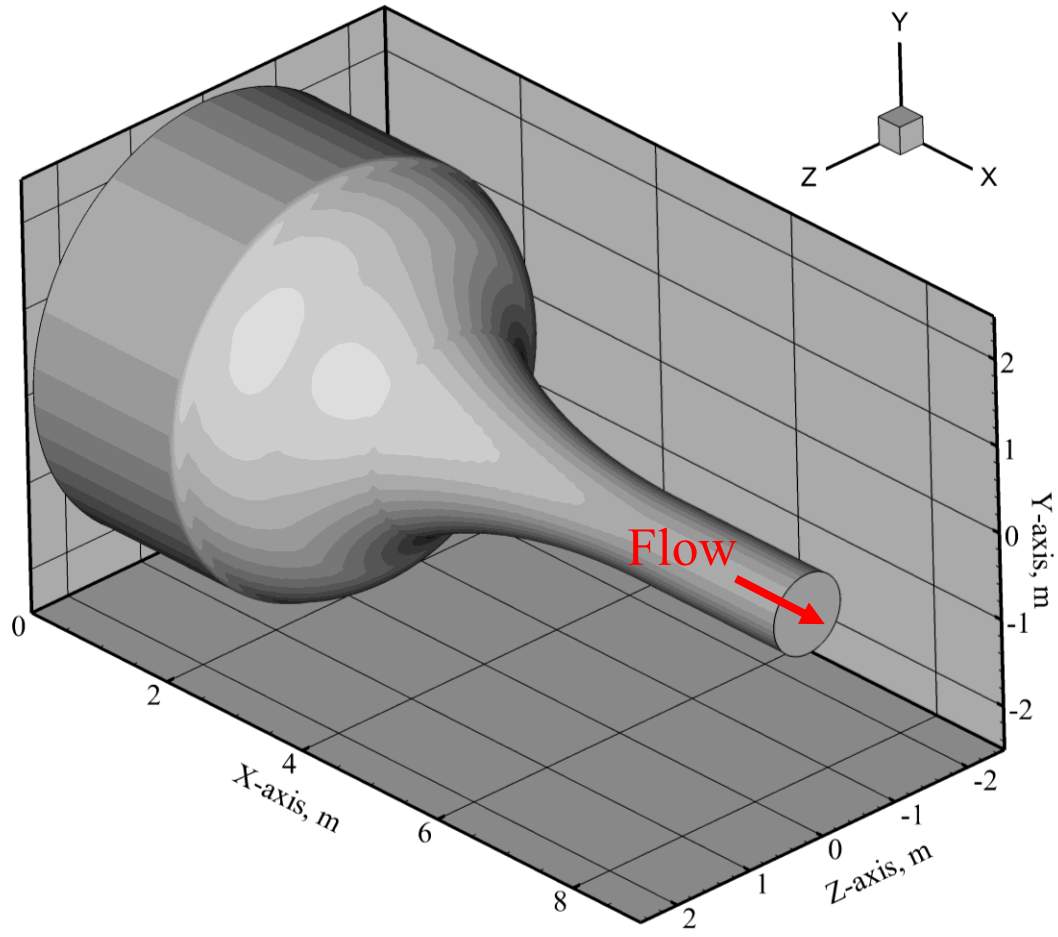
## Notes:

- Aft-looking-forward
- Cartesian coordinate in inches
- Experiment points in red ovals compared to simulation predictions

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# Geometry and Mesh Generation



## Notes:

- PSL geometry modeled from Inlet Plane to Exit Plane
- Meshing via Pointwise
- 2.96 million structured hexagonal cells
- Spray bar system geometry not included

# CFD Simulation – Key Parameters

- Steady-state simulations run with ANSYS Fluent
- Utilized Discrete Phase Model (DPM) to simulate cloud particles
- Fully coupled energy and mass exchange between air and cloud simulated
- Individual nozzles ejecting water droplets in a cone simulated
- PSD approximated using Rosin-Rammler distribution
- Standard k-epsilon viscous flow with 10% turbulence used at inlet BC
- Discrete Random Walk Turbulent Dispersions
- Freezing was not simulated

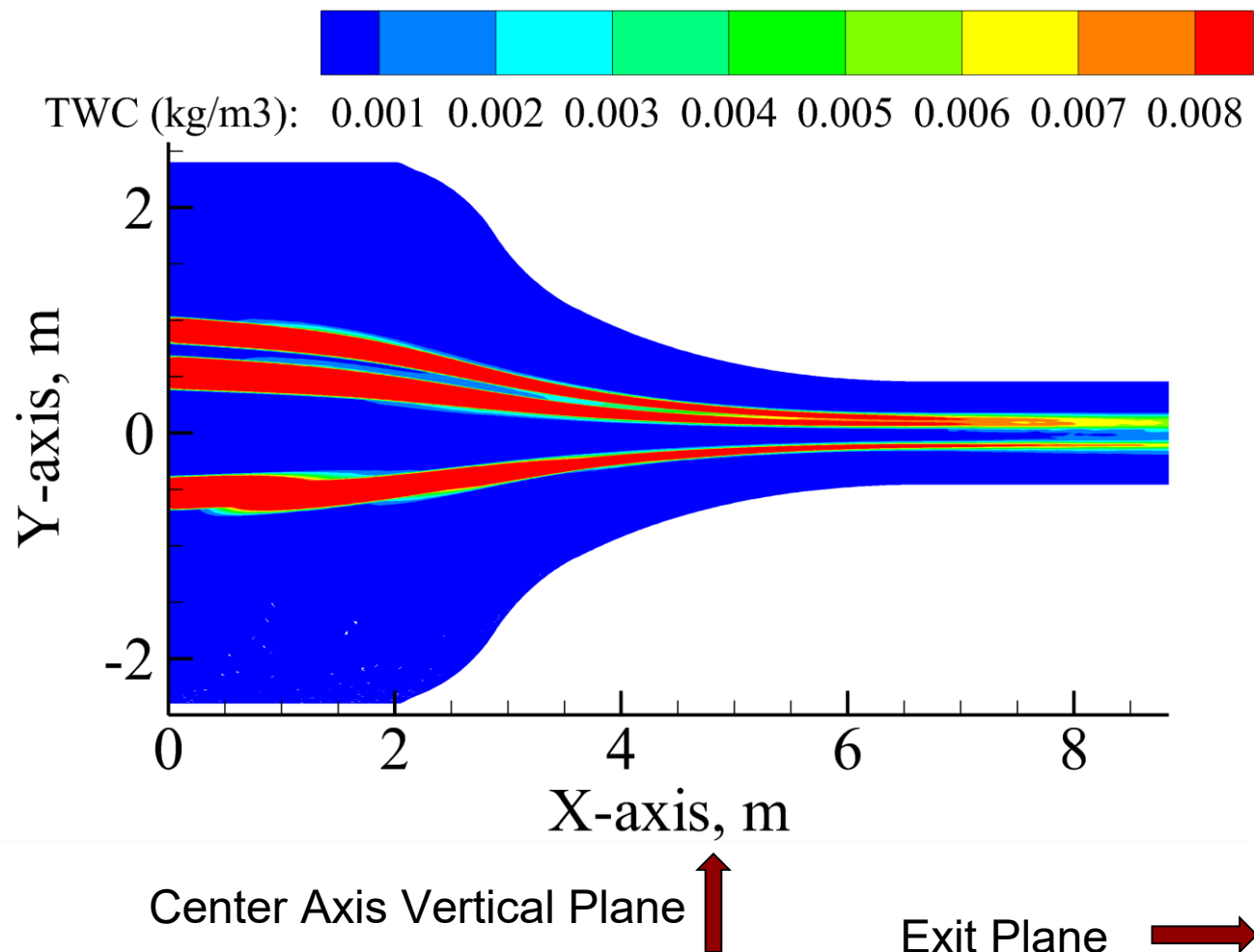
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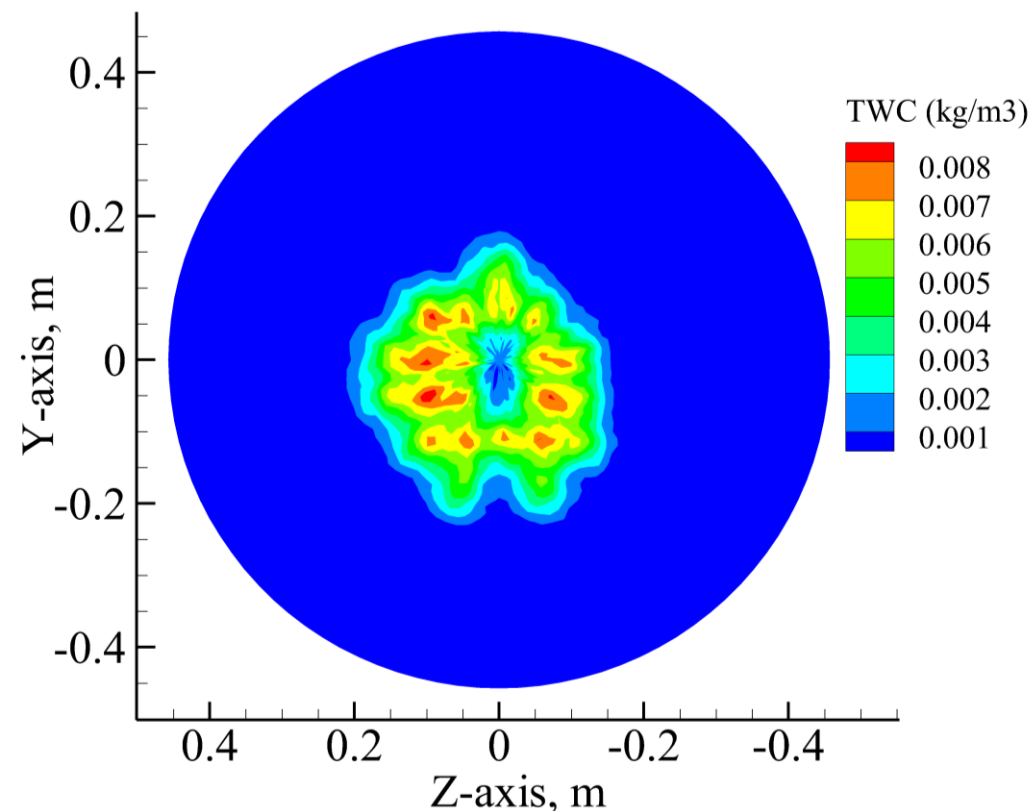


# CFD Simulation Results – Cond II (Water Content)



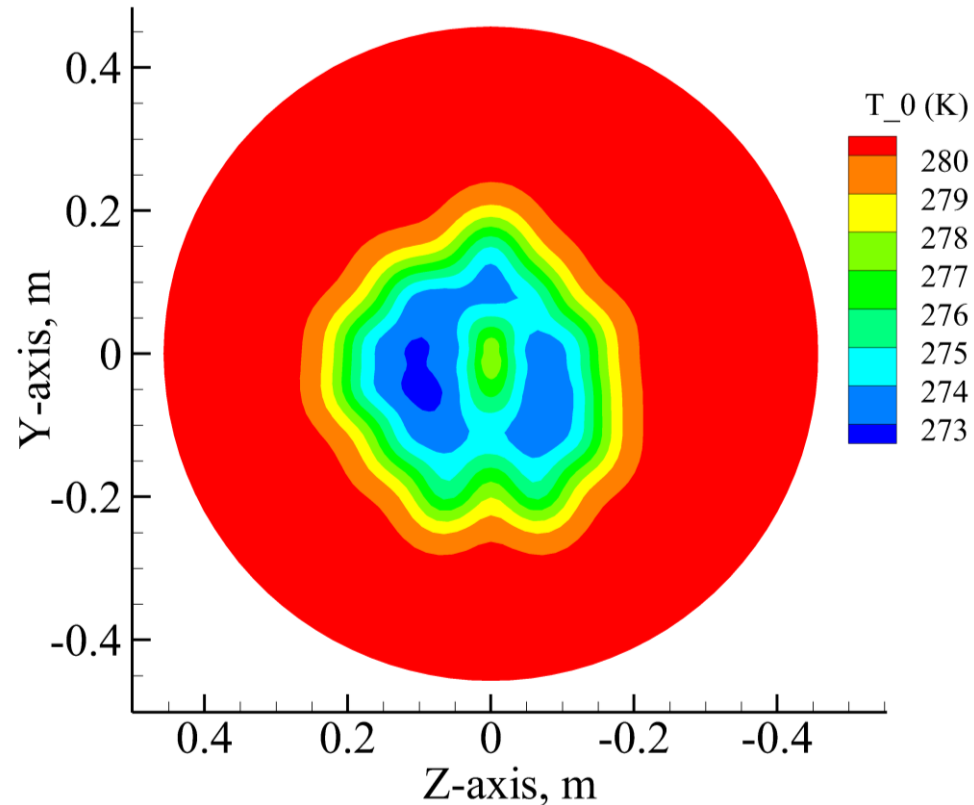
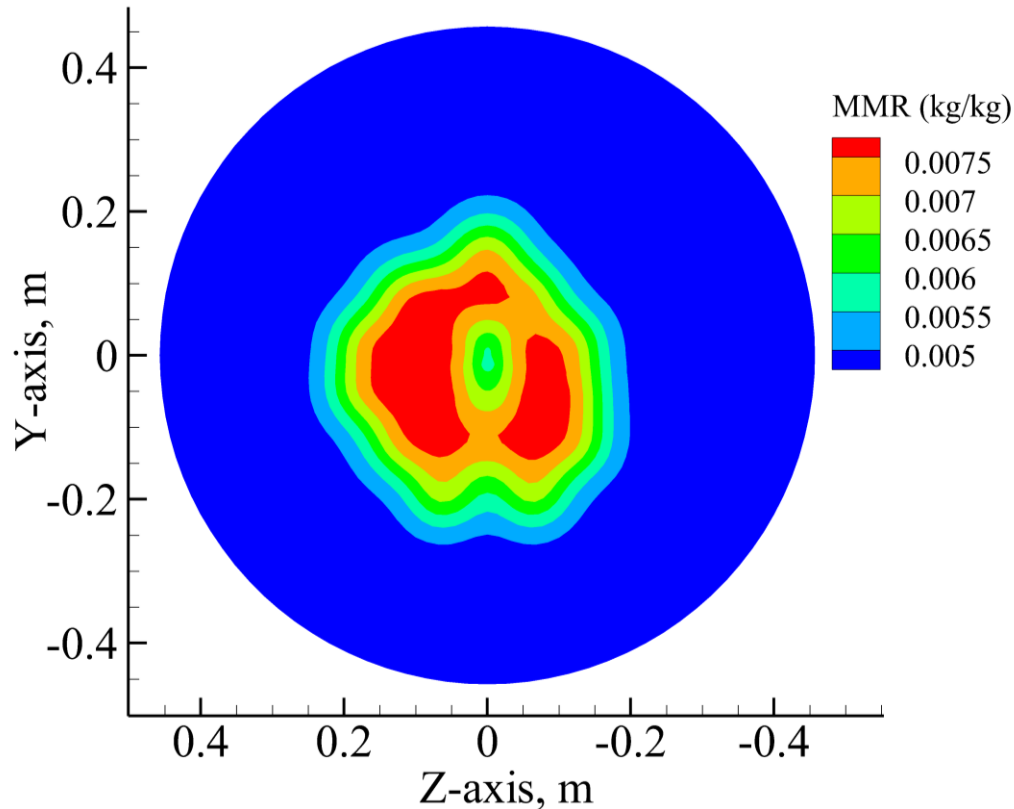
## Notes:

- Radial variation due to centralized nozzle configuration at inlet
- “Donut Shape” predicted





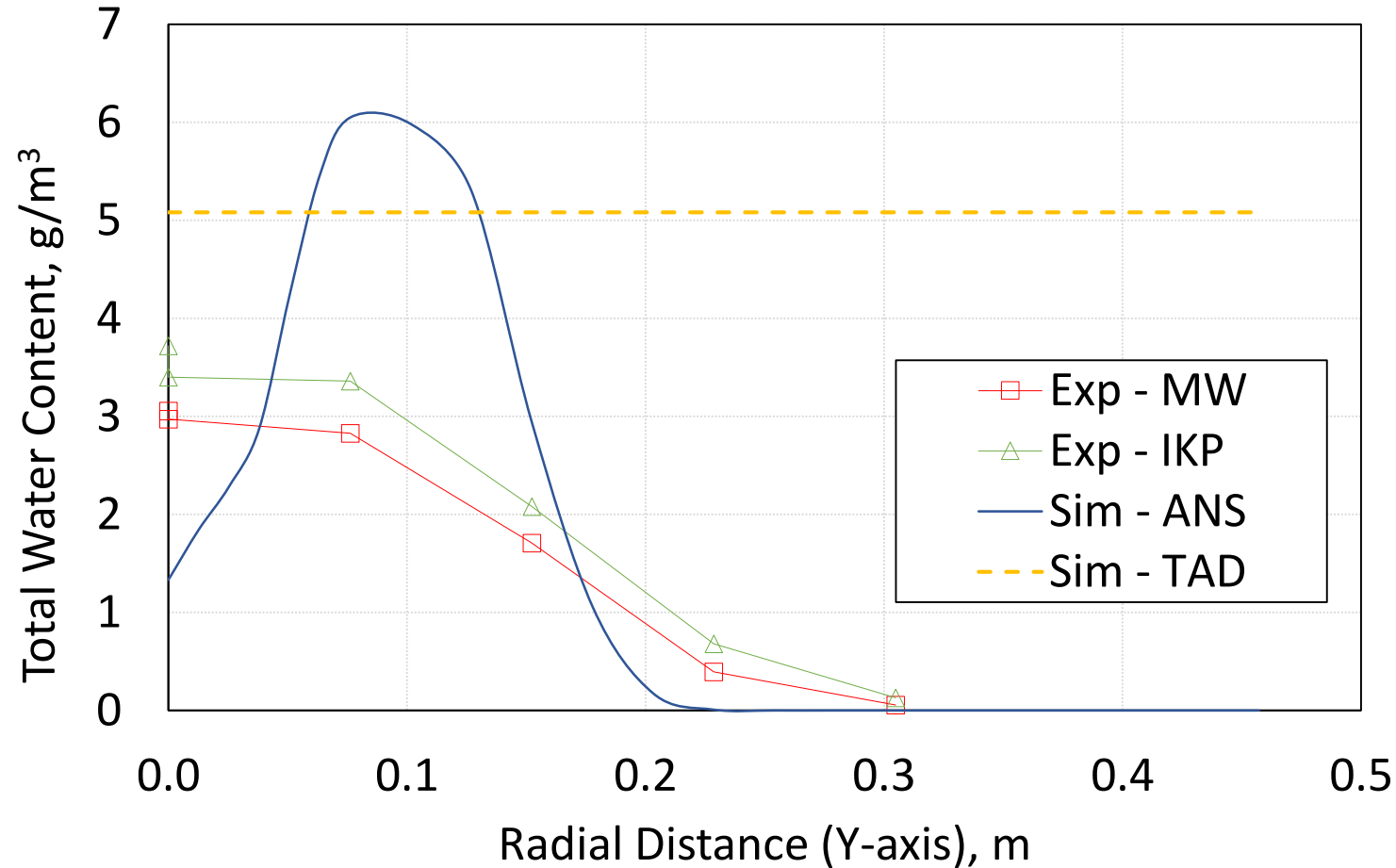
# CFD Simulation Results – Cond II (Humidity and Temp)



## Notes:

“Donut hole”  
less prominent  
with air mass  
related  
conditions

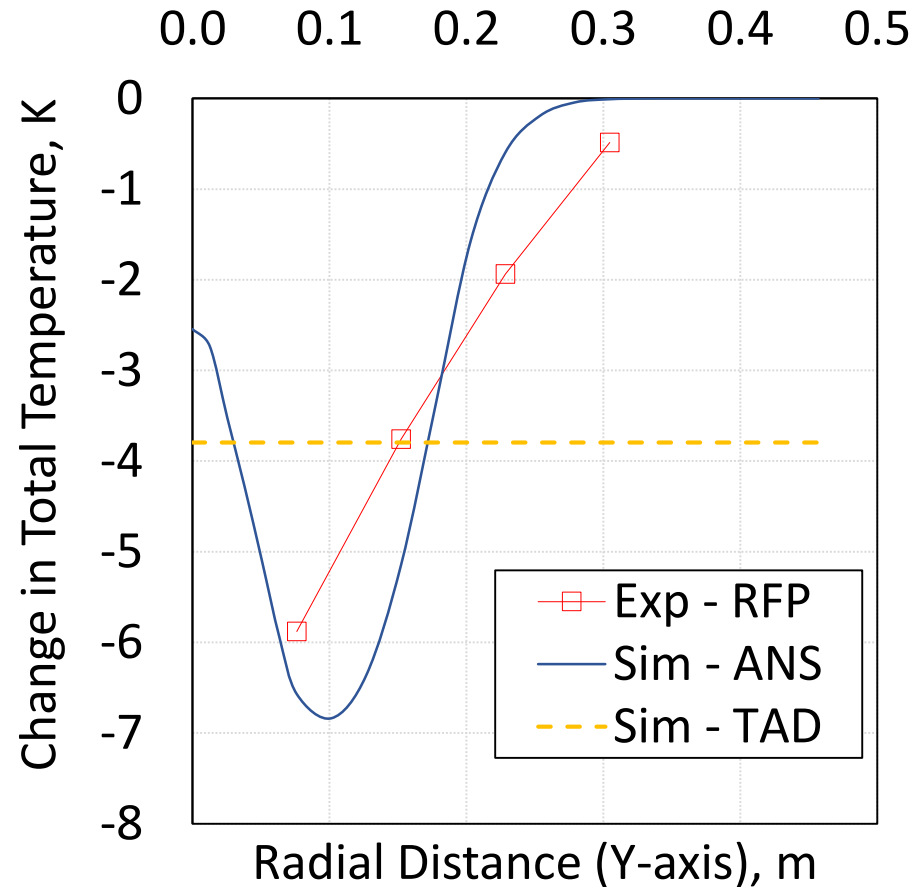
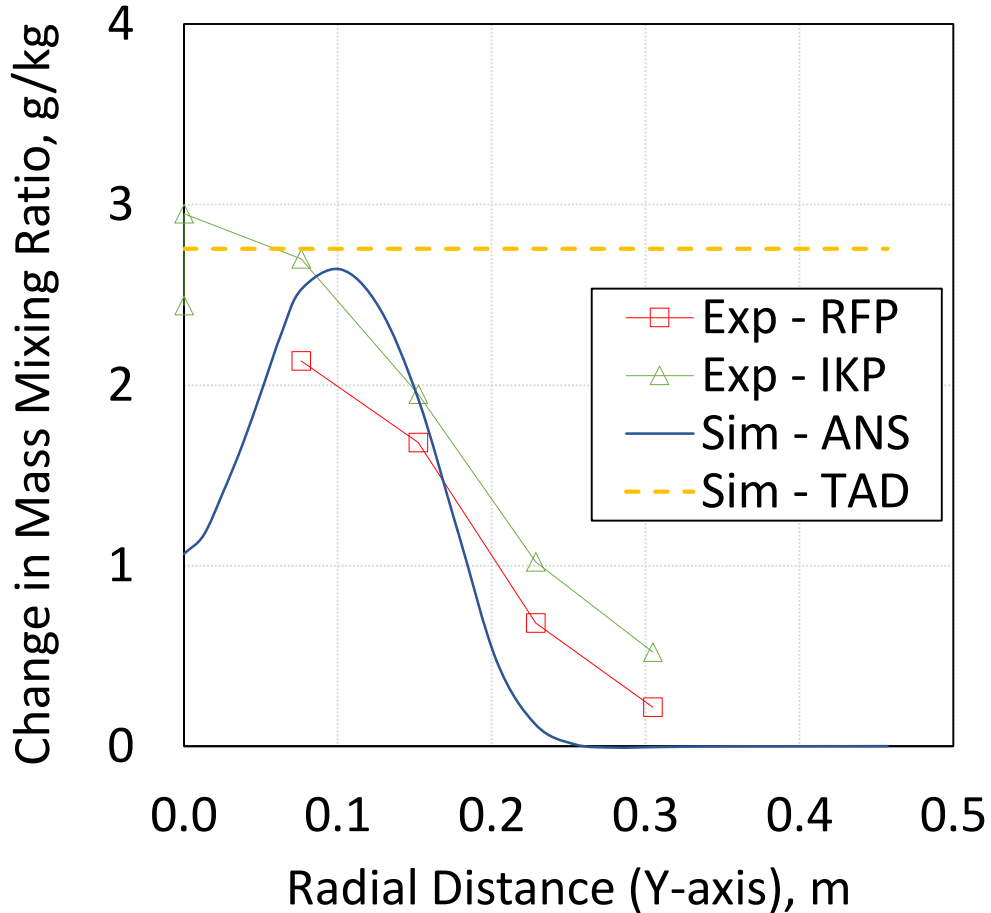
# Sim/Exp Comparison – Cond II (Water Content)



## Notes:

- $U = 135 \text{ m/s}$   
 $\text{TWC}_{e,\text{bulk}} = 2 \text{ g/m}^3$
- Simulation peak TWC values correspond to location of nozzles in the center vertical axis

# Sim/Exp Comparison – Cond II (Humidity and Temp)

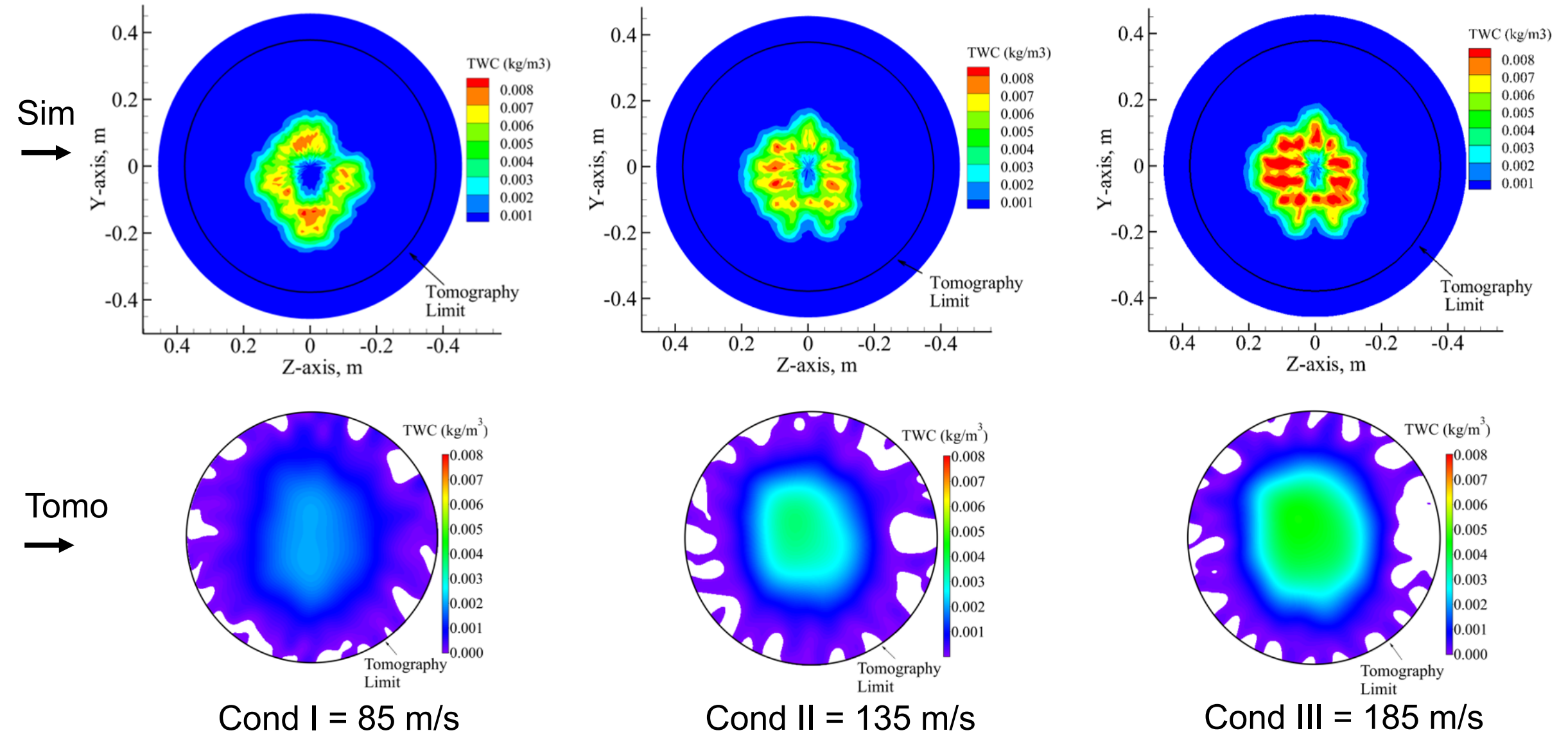


## Notes:

Change =  
cloud on – cloud off

No centerpoint  
measurement for  
RFP

# Sim/Exp Comparison – Cond I, II, III (Tomography)



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# Summary

- Fully coupled 3D CFD model of the PSL icing wind tunnel was developed
- Simulations of icing cloud development were compared with experimental data
- Simulation did not predict as much cloud dispersal
  - Simulating spray bar geometry may capture greater dispersal
- Simulation captured humidity change and temperature change fairly well
  - Did not predict cloud dispersal (particles), but did capture evaporation (molecular)
- Some cloud concentrating aspects captured when velocity increased

# Acknowledgments

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# Thank you

